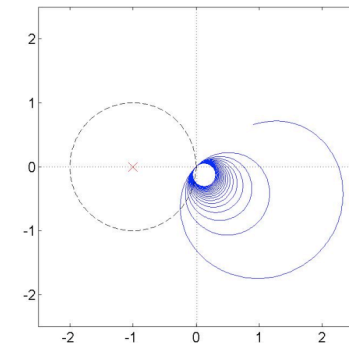
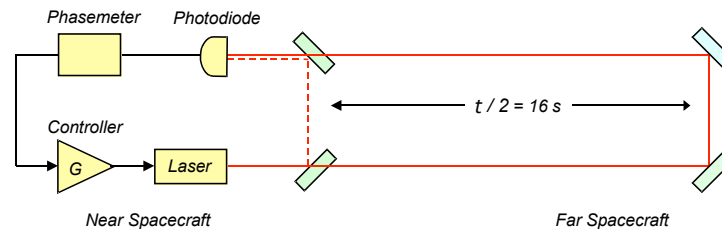
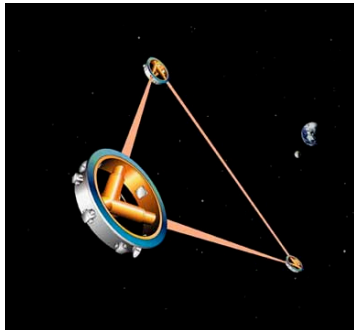


Arm Locking in a LISA-like Hardware Model

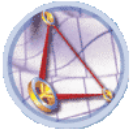


James Ira Thorpe & The UF LISA Group
University of Florida

6th International LISA Symposium
Goddard Space Flight Center - Greenbelt, MD
June 23rd, 2006

-Supported by NASA/OSS –

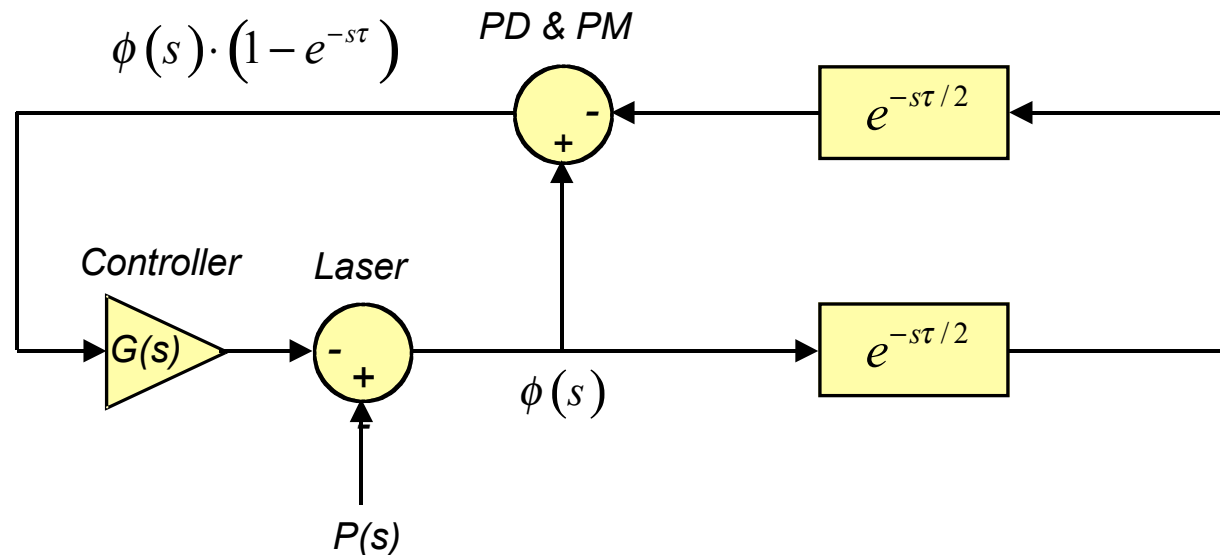
BEFS04-0019-0019



Arm-Locking*

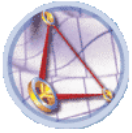


- Use LISA arm as a frequency reference



- Open-Loop Transfer Function $T_{OL}(s) = G(s) \cdot (1 - e^{-s\tau})$
- No signal at Fourier frequencies $f = f_n \equiv n / \tau \quad n = 1, 2, 3 \dots$
 - no phase noise suppression
 - no GW signal

*Sheard, et. al “Laser Frequency Stabilization by locking to a LISA arm” *Phys. Lett. A* 2003



Controller Design



System Transfer Function

$$T_{sys}(s) = \frac{1}{s} (1 - e^{-s\tau})$$

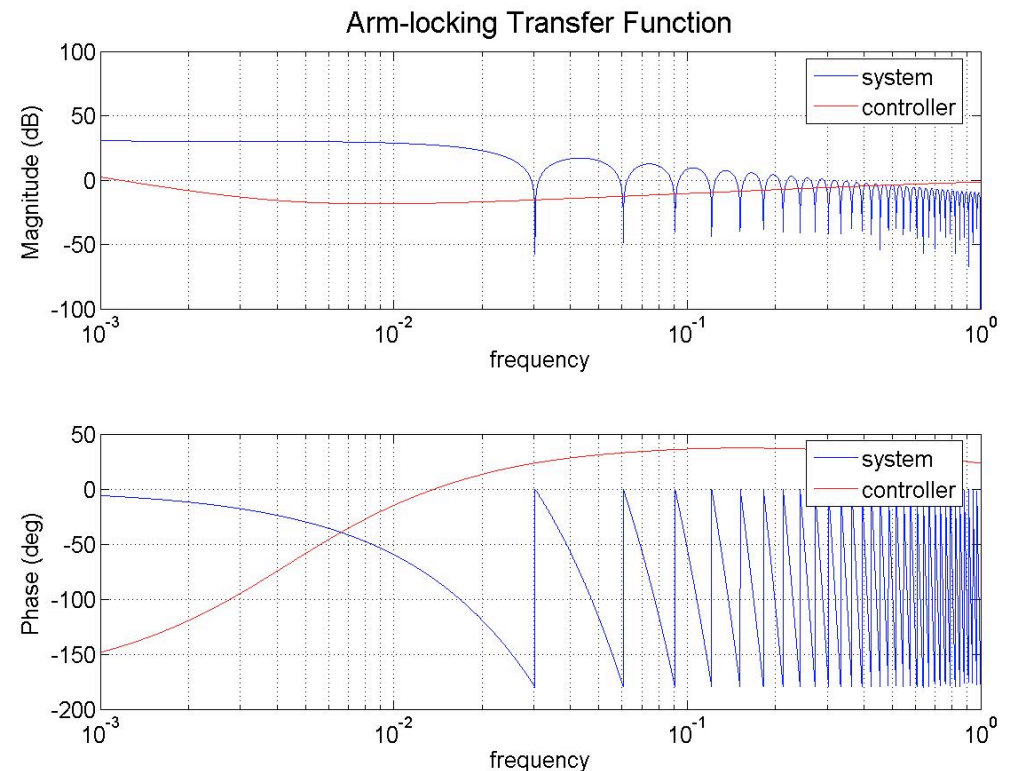
Zero phase margin at $f = f_n$

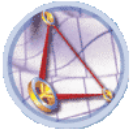
If $f_{UG} > f_1$, controller must provide phase margin.

Controller of s^α provides phase margin of $\alpha\pi/2$

$f \ll f_1$, $\alpha = -1, -2$ large gain at low frequencies

$f_1 \leq f < f_{UG}$, $0.1 \leq \alpha \leq 0.8$ phase margin at high frequencies

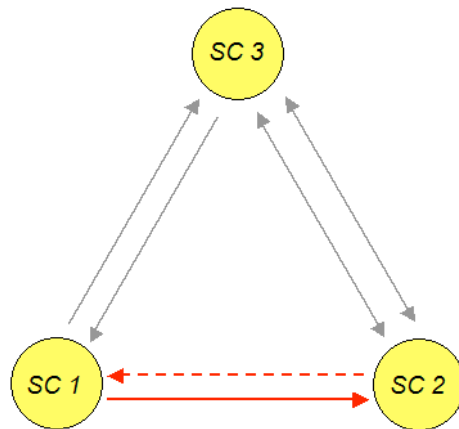




Arm-locking Variants



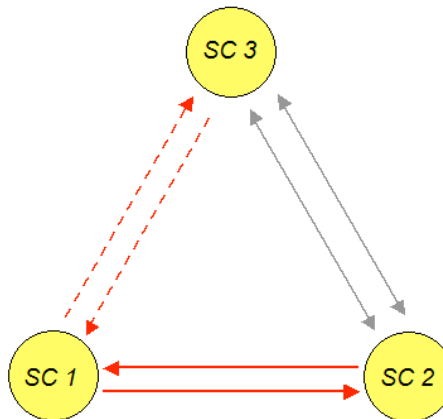
Single



$$f_1 \approx 30\text{mHz}$$

(Round-trip arm length)

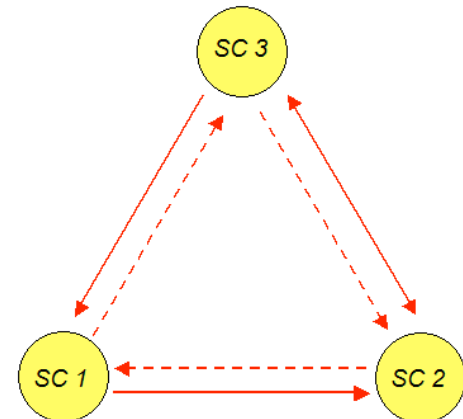
Common



$$f_1 \approx 3\text{Hz}$$

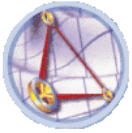
(Difference between arms)

Sagnac



$$f_1 \approx 20\text{kHz}$$

(constellation rotation)



Closed Loop Dynamics



- 🎯 Closed-Loop Transfer Function

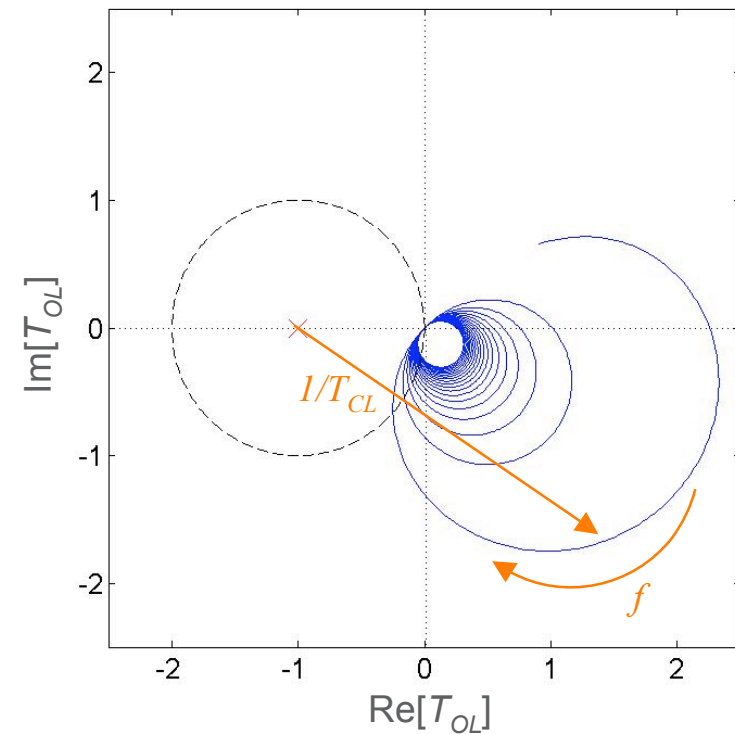
$$T_{CL}(s) = \frac{1}{1 + T_{OL}(s)}$$

- 🎯 Noise suppression when

$$|1 + T_{OL}(s)| > 1$$

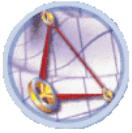
- 🎯 Noise enhancement when

$$|1 + T_{OL}(s)| < 1$$



Plot values: $G = 2s^{-1/2}$, $\frac{1}{20\tau} \leq f \leq \frac{5}{\tau}$

Noise suppression at most frequencies, narrow noise spikes near $f_n = n/\tau$

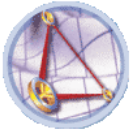


Questions & Concerns

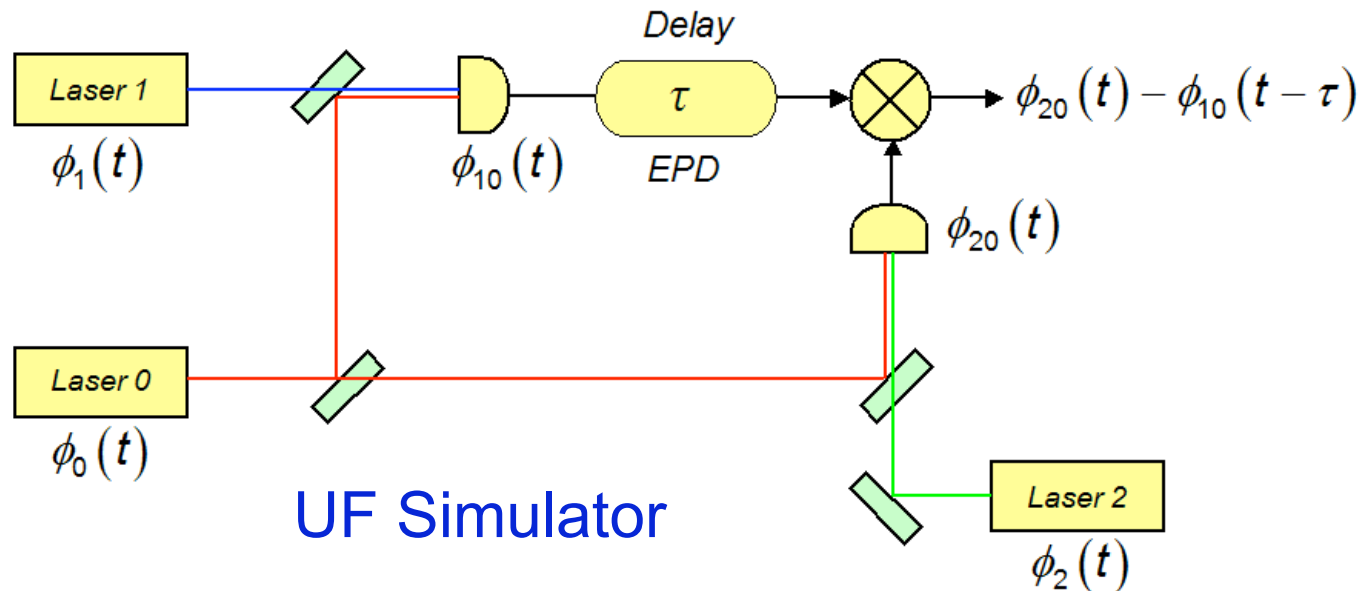


- Stability
 - steady-state
 - transient
- Interaction with other IMS systems
 - reference cavity
 - phase meter
 - transponder locks
- Realization of control filter

Want to face these and other problems? **Try to build it!**

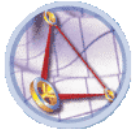


Modeling LISA Interferometry

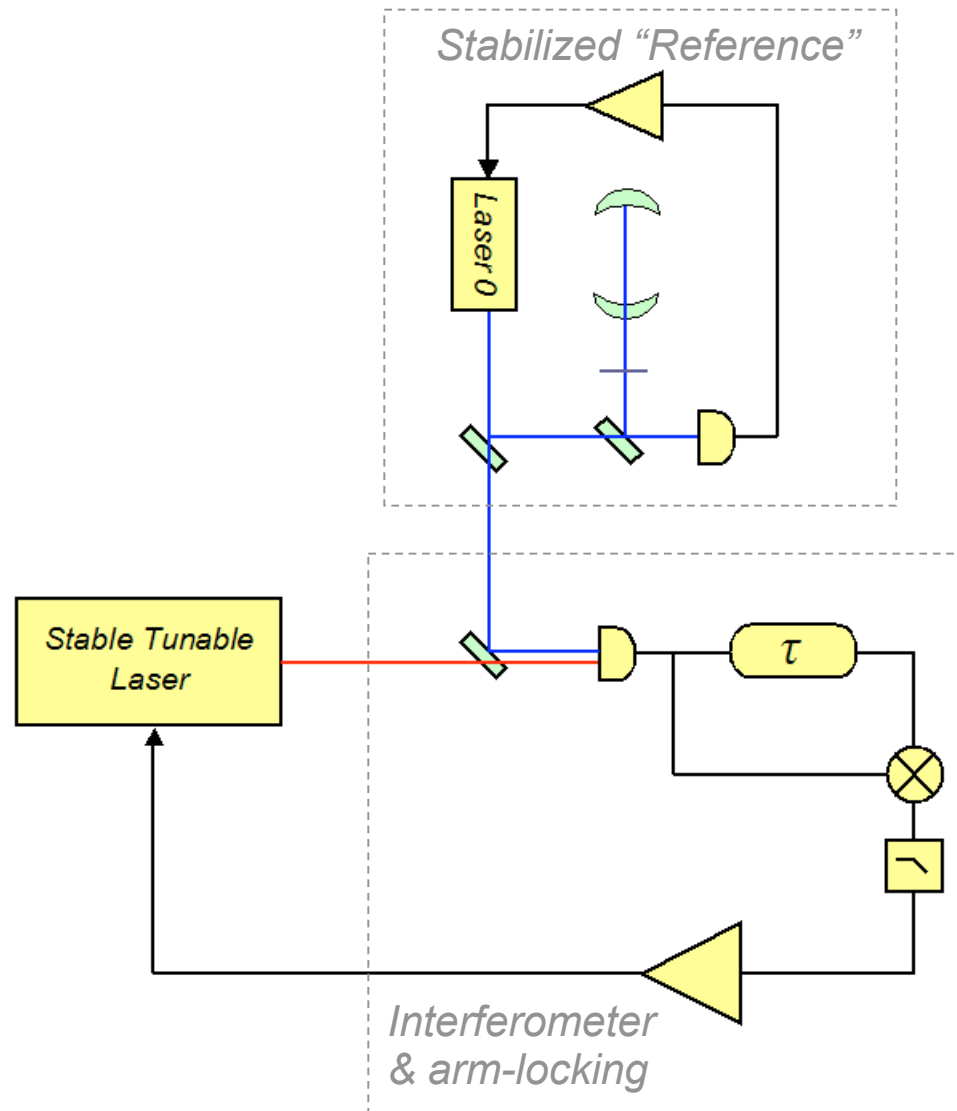


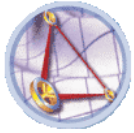
UF technique:

- Laser Phase replaced by beat note phase
- Beat note phase delayed electronically (EPD).
- LISA photodiodes replaced by electronic mixers.



An EPD-based model of Arm-Locking



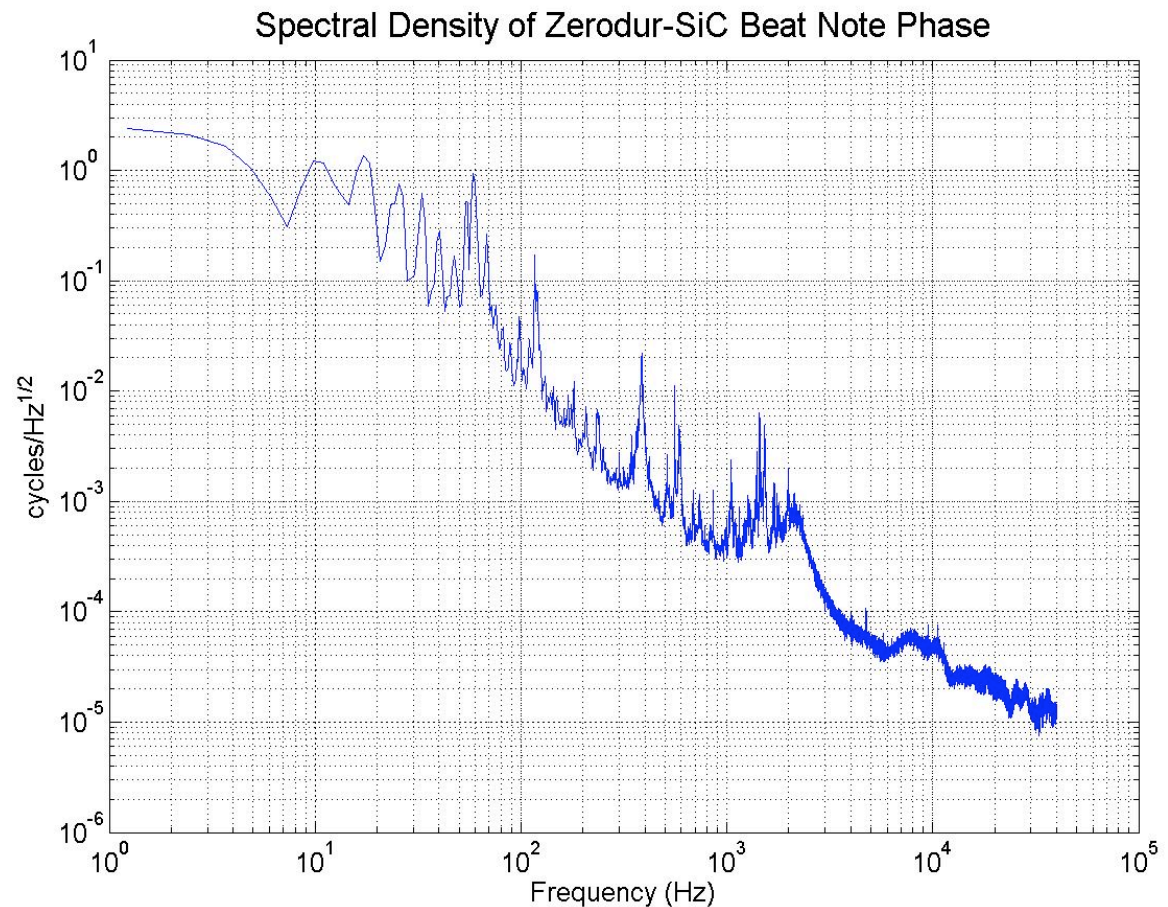


System Parameters – Phase Noise*

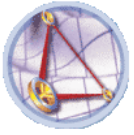


Noise Sources:

- SiC cavity
- Zerodur Cavity
- Phase Lock Loop
- RF Oscillators
- Control Electronics
- etc



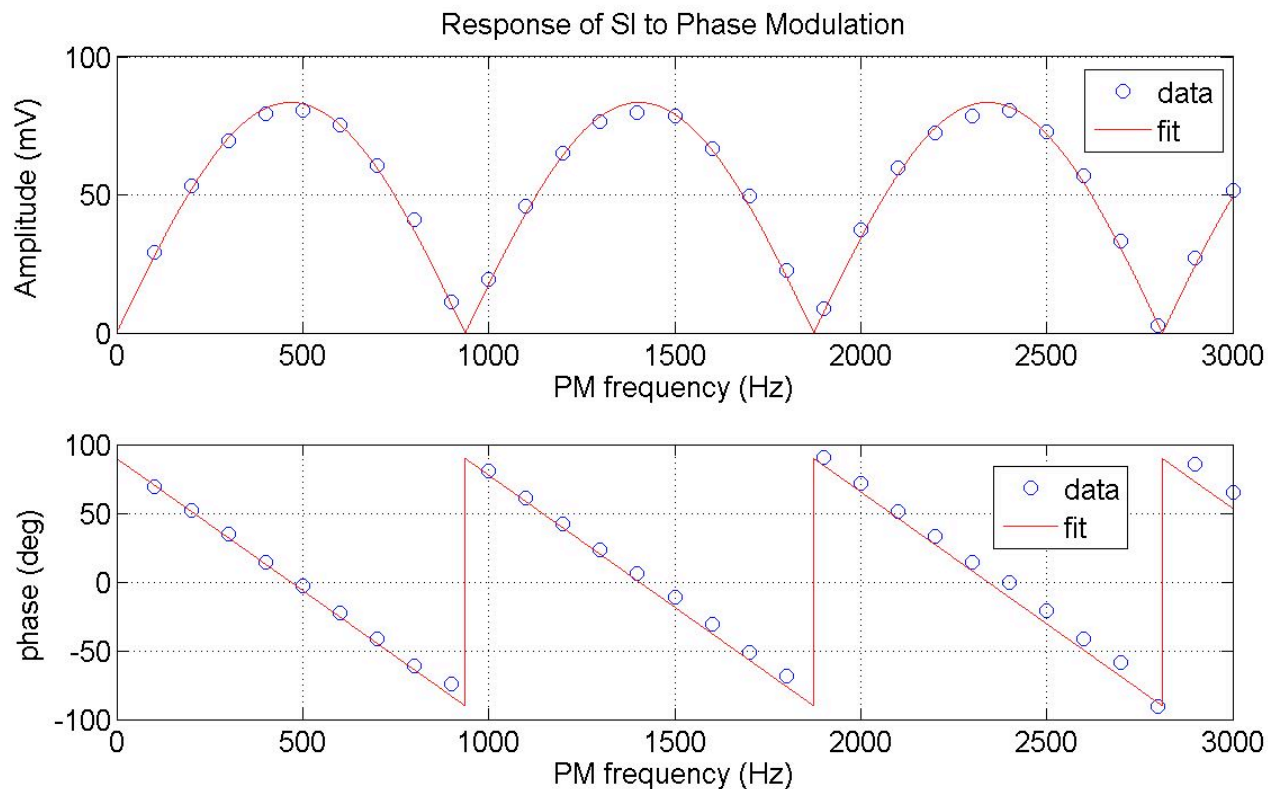
* Cavity systems built by Rachel Cruz & Co.

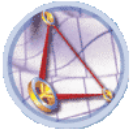


System Parameters – Interferometer



- Analog “phasemeter” has small dynamic range
- EPD using 25 MHz digitization rate, delay of 1.065ms, $f_1 = 939\text{Hz}$



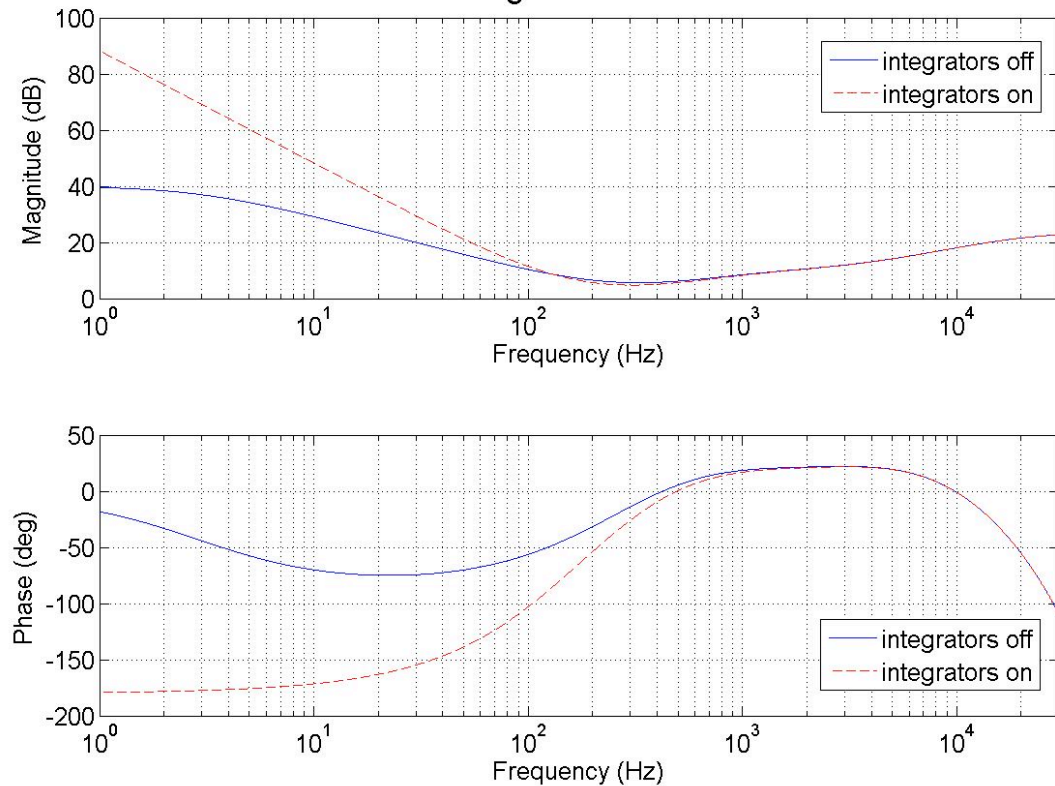


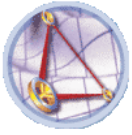
Controller



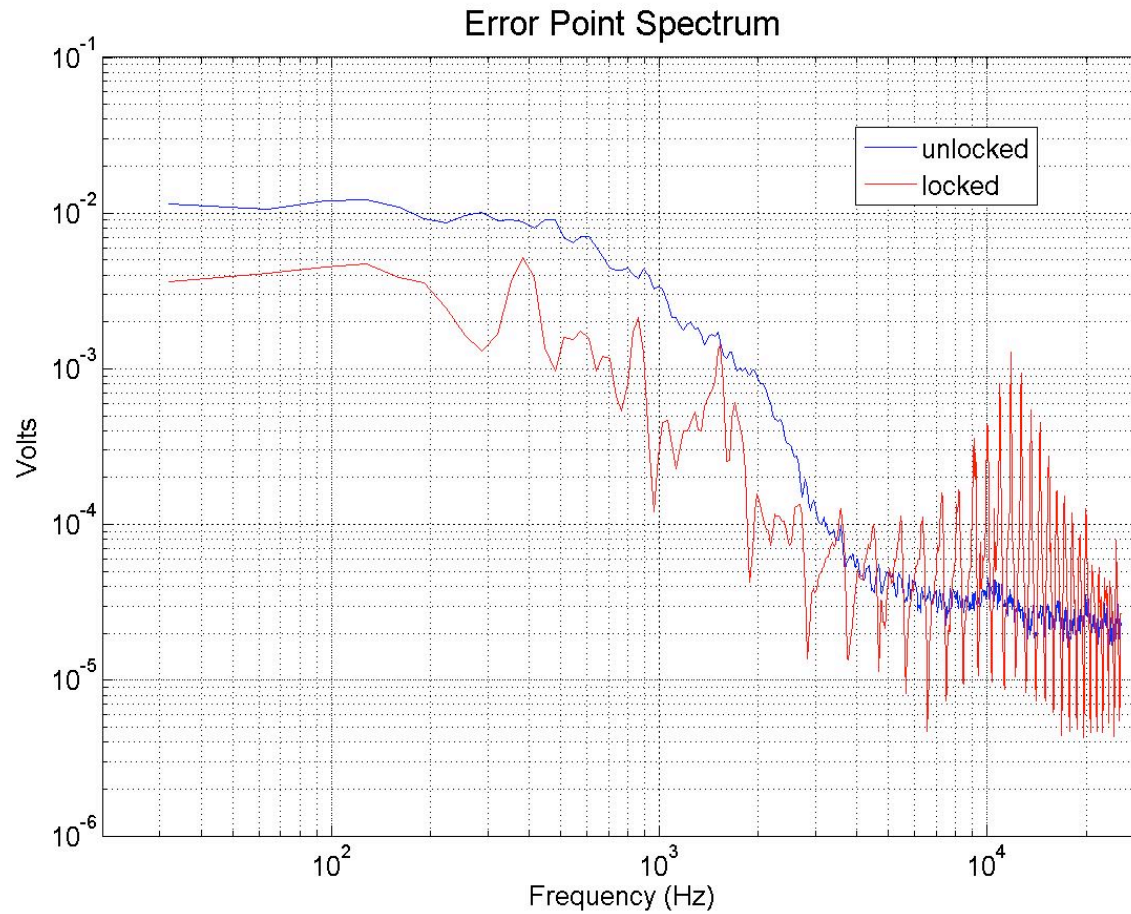
- Hybrid digital/analog system
- Bandwidth limited by delays in digital system.
- Additional integrators add gain at low frequencies

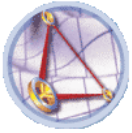
Arm-Locking Controller Bode Plot





Results – Error Point Noise

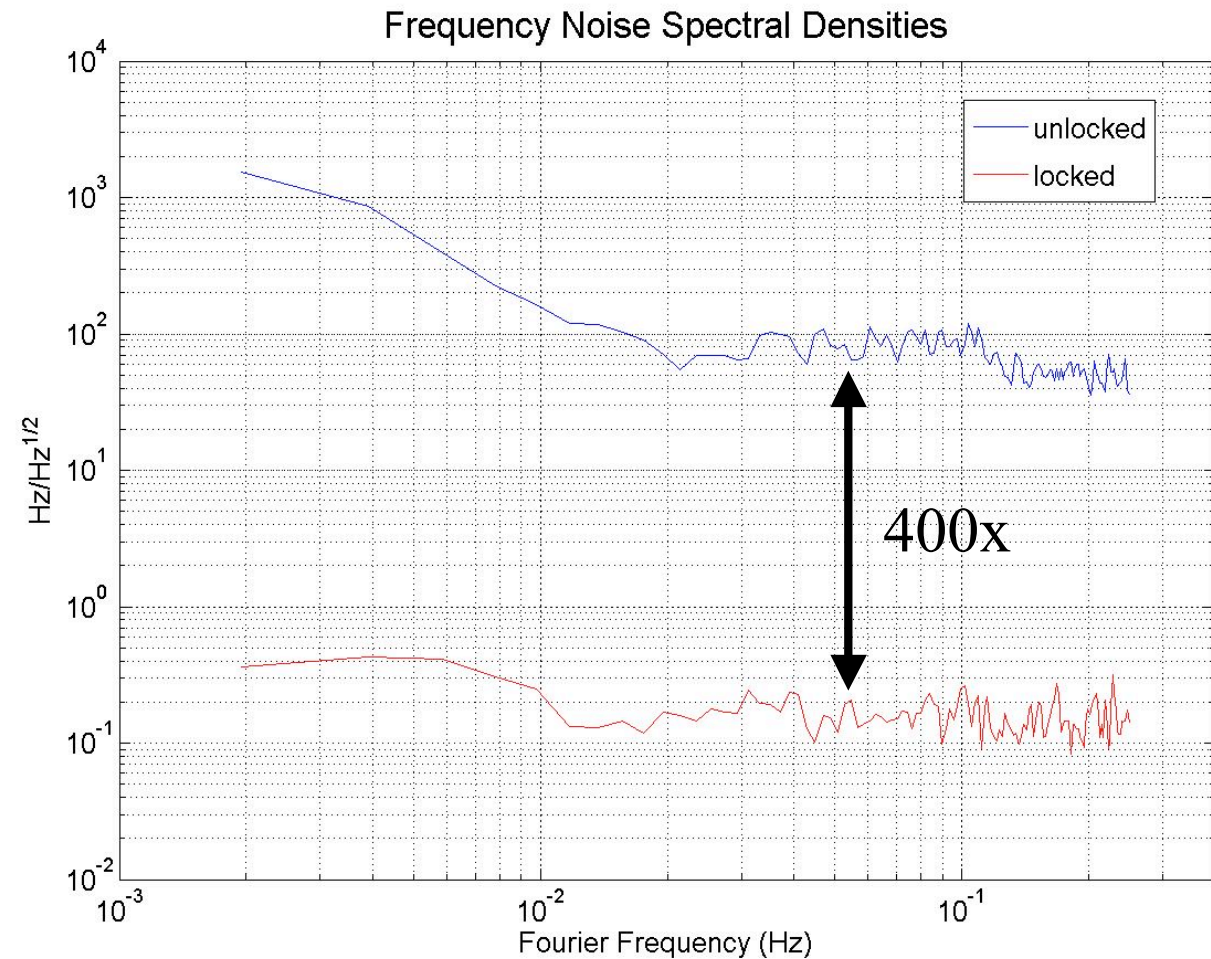


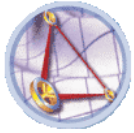


Results – Frequency Noise



🌐 Out-of-loop measurement of primary beat note using frequency counter.

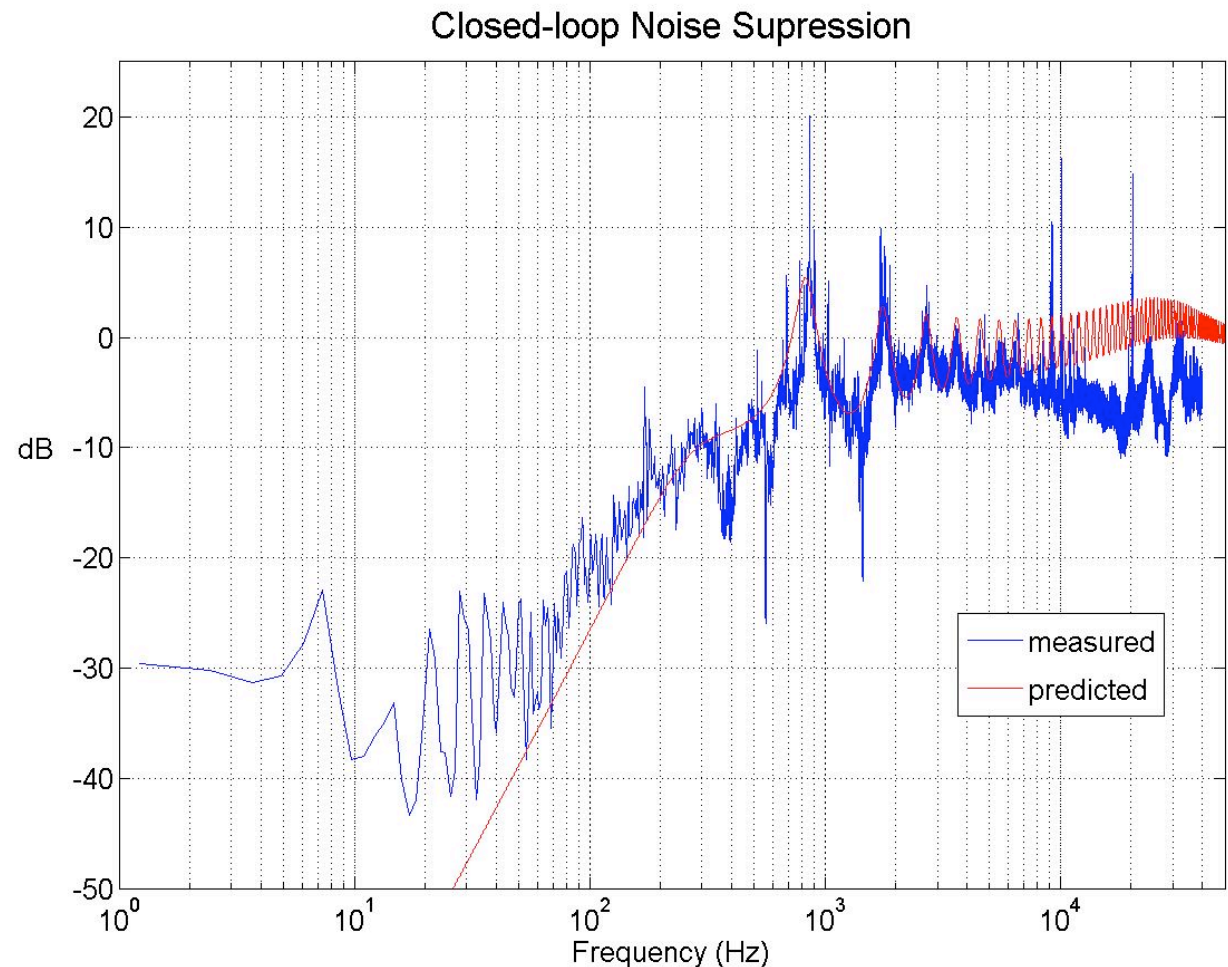


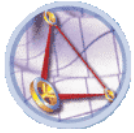


Results – Phase Noise



- Out-of-loop
- Primary beat note demodulated to 10kHz
- Phase of 10kHz signal measured using software phase meter.

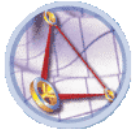




Improvements



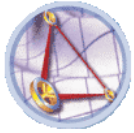
- Improve pre-stabilization
 - return to Zerodur-Zerodur beat (long-term drift)
 - improve electronics (high-frequency noise)
 - reduce acoustic coupling (high-frequency noise)
- Increase controller bandwidth
 - faster digital electronics
- Increase linear range
 - add hardware phase meter in the loop
- Increase time delay to LISA-like levels
 - contingent upon above results



Summary



- Arm-locking could be used to relax requirements on laser stabilization and TDI in LISA
- But it should be tested! (need to model large OPLs)
- UF technique provides model with realistic noise and realistic transfer functions.
- Arm-lock achieved with 1ms delay, but bandwidth is low
- Improvements in system components should allow demonstration of arm-locking with improved performance and full LISA delays.



UF LISA Team



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**Ira
Thorpe**



**Rachel
Cruz**



**Alix
Preston**



**Sridhar
Reddy**



**Rodrigo
Delgadillo**



**Shawn
Mitryk**



**Michael
Hartmann**

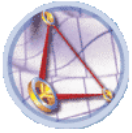


**Gabriel
Boothe**



**Aaron
Worley**





Results – Comparison

